

# Gamma-Ray Bursts and TeV quantum gravity

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**Abstract** Limitations on the multi-dimensional TeV-scale quantum gravity model by Arkani-Hamed, Dimopoulos and Dvali (1998) and on model by Dvali, Gabadadze, Porrati (2000) are obtained from an analysis of gamma-ray bursts at cosmological distances (relativistic fireball model).

## 0.1 Extra dimensions and their manifestations

Recently an idea of large extra dimensions become very popular due to benefits it provides in solving of hierarchy problem of particle physics (the fundamental Planck mass scale  $\sim 10^{18}$  GeV relevant for gravitation is much larger than electroweak scale  $\sim 1$  TeV (e.g. [2] for a review). These theories assume that the Standard Model particles are localized in a (3+1)-dimensional "brane" embedded in a compactified space (bulk) with large (or infinitely large) extra dimensions. In these scenarios, the fundamental gravity scale is no more the conventional Planck mass, which determines the observable weakness of the Newton gravitational constant  $G_N$ . The latter turns out to be defined by the quantum gravity scale  $M_*$  of the corresponding theory.

In such a frame, one of the phenomenological manifestations of the existence of large (or infinite) extra dimension(s) is an additional cooling of

hot plasma due to emission of Kaluza-Klein massive gravitons into the bulk (ADD model, [1]) or excitation of stringy Regge states (DGP model, [4]): which are allowed to propagate freely in the bulk and carry away energy from the brane. Though this coupling is suppressed by 4-dimensional Planck mass scale, at high enough energies it may become noticeable, and it is conceivable to observe events with energy missing.

## 0.2 Constraints on the models parameters

There are number of restrictions on fundamental gravity scale  $M_*$  of models with extra dimensions from high energy phenomena in astrophysics and from the processes in the early Universe [1, 2]. The basic constraints come from SN1987a cooling, BBN, etc... (see [1, 2, 7, 8, 9] for more detail). Here we consider constraints the very existence of cosmological gamma-ray bursts (GRB) imposes on some modern theories of gravity. As an example, we examine the ADD theory of multi-dimensional gravity with quantum gravity scale at TeV energies ([1]), and more recent DGP 5D-gravity of infinite-volume flat extra space with  $10^{-3}$  eV quantum gravity scale ([4, 5]).

The most viable model of GRB is the relativistic fireball model, which is apparently confirmed by the bulk of GRB studies in a wide range of wavelengths from radio to gamma-rays (see Dr. M.Vietri's lecture, this volume; [11, 13]). In a GRB, a huge energy ( $10^{51} - 10^{53}$  ergs) in gamma-rays ( $E_\gamma \sim 100$  keV – 10 MeV) is released in a short time (typically observed  $\Delta t_\gamma \sim 10 - 100$  s). This energy, liberated in a small region  $\sim 10^6 - 10^7$  cm in size, creates a photon-lepton "fireball" with a very high energy densities. For the characteristic energy  $E_{53} = \Delta E_\gamma / 10^{53}$  erg and the initial size  $r_6 = r_0 / 10^6$  cm, the initial temperature of the optically thick fireball is  $T_f \simeq 116(\text{MeV}) E_{53}^{1/4} r_6^{-3/4}$ . The photon number density (as well as of relativistic leptons) is  $n_\gamma \simeq 4.3 \times 10^{37} (\text{cm}^{-3}) (T/100 \text{ MeV})^3$  and diverse photon-photon and photon-lepton processes intensively occur. Thus the GRB fireballs can be potentially useful to test high-energy physics at MeV scales.

In the ADD scenario, the 4D Planck mass is related to the compactification radius  $r_n$  and fundamental gravity scale  $M_*$  as  $M_P \sim r_n^n M_*^{n+2}$ , where  $n$  is the number of extra dimensions. The emission of KK-gravitons in the bulk in photon-photon interactions (relevant to GRB fireballs) has a cross

section ([1])

$$\sigma_{\gamma\gamma} \sim \frac{1}{16\pi} \left( \frac{T}{M_*} \right)^n \frac{1}{M_*^2}$$

i.e. the KK-luminosity becomes

$$(dE/dt)_{KK} \sim n_\gamma^2 \sigma_{\gamma\gamma} c \epsilon_{KK} \propto T_f^{7+n} / M_*^{2+n}$$

(here  $\epsilon_{KK} \sim 2.7T_f$  is the typical KK-graviton energy).

If the emission of KK-gravitons effectively cools the fireball before its initial thermal energy is converted into the kinetic energy of the baryons, the required high Lorentz-factors can not be attained, and no GRB with the observed properties can be produced. This implies that the emission of KK-gravitons in the fireball meets the condition  $r_0/c < \Delta E_\gamma / (dE/dt)_{KK}$ . Putting all quantities together, we arrive at the following constraints:

$$n = 2 : \quad M_* > 2(\text{TeV}) E_{53}^{5/16} r_6^{-11/16},$$

$$n = 3 : \quad M_* > 0.25(\text{TeV}) E_{53}^{3/10} r_6^{-7/10}.$$

These are weaker than the limits inferred from SN1987a neutrino burst ( $M_* > 30$  TeV for  $n=2$ ) and from cosmological considerations [1, 7].

More interesting is the case of DGP model. In this framework, the weakness of an observable gravity is explained by the high cut-off of the Standard Model  $M_{SM}$  localized on the brane. In contrast to the ADD model, the large value of the observable  $M_P$  is determined by  $M_{SM} \gg M_*$  rather than  $M_*$ . Now the emission of massive KK-gravitons into the bulk is strongly suppressed. Instead, the possibility to produce an exponentially large number of Regge states at very low energy appears. At  $T \ll 1$  TeV, the total rate of the production of stringy Regge states is determined by the 2-d mass level and is ([5])

$$\Gamma_2 \sim E \frac{E^4}{M_*^2 M_P^2}$$

(here the mean energy particle  $E \sim 2.7T$ ). This gives rise to the total Regge state emission rate in the GRB fireball  $(dE/dt)_R \approx 10^{55}(\text{erg/s}) E_{53}^{9/4} r_6^{-15/4}$  and the fireball acceleration constraints would be  $M_* > 0.5(\text{eV}) E_{53}^{5/8} r_6^{-11/8}$ . This is by about two orders of magnitude higher than original lower bound  $10^{-3}$  eV discussed in [5]. If this limit is true, deviations from the Newton gravity are expected at distances smaller than  $r < 1/M_* \simeq 10^{-3}$  mm.

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# Bibliography

- [1] Arkani-Hamed N., Dimopoulos S., Dvali G. 1998, Phys. Lett. B429, 263
- [2] Rubakov V.A., UFN **9**, 913, 2001 (hep-ph/0104152)
- [3] Giudice G.F., Rattazzi R., Wells J.D., 1998, hep-ph/9811291
- [4] Dvali G., Gabadadze G., Porrati M. 2000, Phys. Lett. B485, 208 (hep-th/0005016)
- [5] Dvali G., Gabadadze G., Kolanović M., Nitti F. 2001, hep-ph/0106058
- [6] Esin A., Blandford R. 2000, ApJ 534, L151
- [7] Hannestad S., Raffelt G. 2001, Phys. Rev. Lett. in press, hep-ph/0103201
- [8] Hannestad S., Raffelt G. 2001, hep-ph/0110067
- [9] Biesiada M., Malek B., 2001, astro-ph/0109545
- [10] Postnov K.A. 1999 UFN 169, 545
- [11] Piran T. 1999, Phys. Rep. 314, 575
- [12] Piran T. 2000, astro-ph/0102315
- [13] Piran T. 2001, astro-ph/0104134
- [14] Vietri M. 1995, ApJ 453, 883
- [15] Vietri M., Perola G., Piro L., Stella L. 2000, MNRAS 308, L29
- [16] Waxman E. 2001, astro-ph/0103186